Finnish Maritime Administration

# WAVE STATISTICS FROM THE NORTHERN BALTIC SEA FOR PASSENGER SHIP BOW STRUCTURAL DESIGN SURVEY

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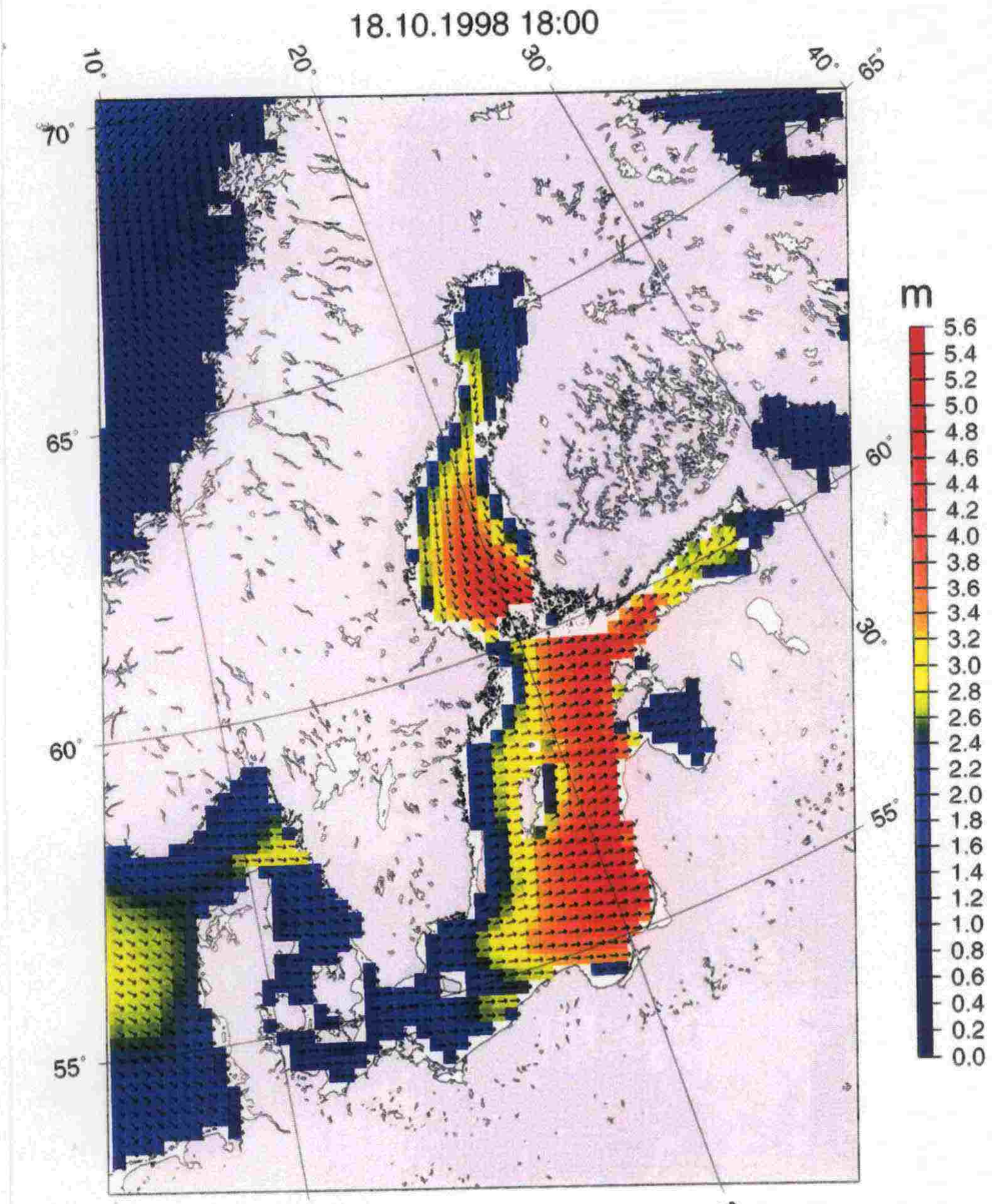

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# 1 Introduction

The Finnish Maritime Administration has ordered from VTT Manufacturing Technology a study "Passenger ship bow structural design agaist wave induced loads at the Norther Baltic". The Finnish Institute of Marine Research (FIMR) as a subcontractor calculated the wave statistics for the study.

During the past three years FIMR has operated a permanent wave buoy in the Northern Baltic Proper. This new measured data, as well as wave model calculations have been used to obtain more accurate statistics than have been available in the past. Previous measurements by FIMR and the Swedish Meteorological and Hydrological Institute (SMHI) during 1982...1986 have been included in the analysis.

The wind conditions and consequently wave conditions vary significantly from year to year. The existing measurements in the Northern Baltic Proper cover 8 years, but the earlier data has considerable gaps. The data still leave considerable uncertainties in the deduced statistics of extreme wave conditions. The aim here is to estimate an upper limit that is unlikely to be found too low when more data becomes available from future measurements.

This conservative approach turned out to be well justified when in December 1999 significant wave height 7.4 m was measured during two different storms in the Northern Baltic Proper. Such wave conditions have been measured only once before in the Northern Baltic Proper. Model calculations suggest that in 39 years such wave conditions have occured only four times, including the three measured events.

Data after September 1999 will not be ready for statistical analysis before this report is due. However, the influence of these December storms on the probabilities of extremes have been analysed and it was found that they do not change the upper limit extrapolation. This extrapolation is the basis of the conclusions of this study.

On the other hand, the most probable extrapolation that was also presented in the draft will change, and it has been removed from this final report.

# 2 Wave climate in the Northern Baltic Sea

## 2.1 General

The wave climates in various parts of the Baltic Sea differ greatly. In the Northern Baltic Proper the typical wave height is roughly half of that in the North Atlantic, whereas in the Gulf of Finland the wave height is limited to roughly one half of the Northern Baltic Proper. The wave climate in the Bothnian Sea is slightly less severe than in the Northern Baltic Proper.

Besides having a less severe wave climate, the Åland Sea, the Gulf of Finland, and the Quark have directionally strongly skewed statistical distributions. In other words, large waves can arrive only from certain directions, and waves tend to arrive from those directions even when the direction of the wind is different. This means that the loads for vessels that are dependent on wave direction may vary even more than the non-directional wave statistics would indicate.

## 2.2 Treatment of missing values and the ice period

It is very difficult to make uninterrupted wave measurements in the open sea. Instrument or transmission failures and ice are the most important reasons for gaps in the record.

Ice introduces a special problem in wave statistics, because the period of missing values caused by ice is by no means random. Especially in the Bothnian Bay the long ice season influences the wave climate. The Bay is at least partly frozen during the season when the wind climate is most severe. Annual statistics and maximum wave height give a distorted — too low — view of the wave climate of the ice-free season. When the sea there is ice-free the waves are higher than they are in an area that has the same annual wave statistics but never has ice. This applies to a smaller extent also to the other areas of the Baltic Sea, and therefore has to be taken into account to avoid inconsistencies in comparisons.

There are at least four different ways to analyse wave climate in areas where there is ice during part of the year:

**A.** Direct statistics.

Only measured data is taken into account. No corrections are made to compensate for the uneven distribution of missing values.

**B.** Formal statistics

Wave height in the presence of ice equals zero. Missing values in other seasons are estimated from the seasonal distributions.

**C.** Ice-free season statistics

Only the part of the year when the sea would be ice-free in an average winter is taken into account when statistics are calculated. Missing values during the ice-free season are estimated from the seasonal distributions.

**D.** Hypothetical "no ice" statistics

Using wave models and wave measurements from winters when the ice period is shorter than normal, hypothetical statistics are calculated to represent the wave climate under the assumption that the sea remains ice-free throughout the year.

Clearly, a different method will be the best one for different purposes. In this report we will present data using methods A and C. Note that when time, rather than a percentage of time, is used in a table, statistics of type B are identical with statistics of type C, except for classes that include zero wave height.

## 2.3 Overview of wave climate in the Northern Baltic Sea

The Finnish Institute of Marine Research (FIMR) has made wave measurements in the Baltic Sea from 1972. The Swedish Meteorological and Hydrological Institute (SMHI) has measured waves from 1979 at Almagrundet and at some other locations, all South from Almagrudet. During the years 1983 - 1986 measurements were carried out at Bogskär as a joint project by FIMR and SMHI.

The periods and the locations of the wave measurements by FIMR are shown in Figure 1.

Table 1: The highest measured significant wave heights.

| | |
|---|---|
| Northern Baltic Proper (Almagrundet) | 7.7 m |
| Northern Baltic Proper (Bogskär) | 6.7 m |
| Northern Baltic Proper (permanent wave buoy) | 7.4 m |
| Gulf of Finland (Kalbådagrund) | 4.0 m |
| Southern Bothnian Sea | 5.5 m |
| Bothnian Bay | 3.1 m |

The above values of significant wave height $H_s$ (defined as $H_s = H_{m_0} = 4\sqrt{m_0}$) are the highest actually measured. They are not adjusted for the differences in measuring times or for the differences in the length of the ice season. Table 1 thus represents statistics of type A. It gives a somewhat misleading impression — too low — of the wave climate, especially in the Bothnian Bay. In Table 1 the data from the Northern Baltic Proper permanent wave buoy cover the measurements from September 1996 to December 1999, including the severe storms in December 1999.

Table 2: The most probable values of the maximum individual wave height at the measuring point during the wave measurements.

| | |
|---|---|
| Northern Baltic Proper (Almagrundet) | 14 m |
| Northern Baltic Proper (Bogskär) | 12 m |
| Northern Baltic Proper (permanent wave buoy) | 13.3 m |
| Gulf of Finland (Kalbådagrund) | 7 m |
| Southern Bothnian Sea (Sandbäck) | 10 m |
| Southern Bothnian Bay (Ulkokalla) | 5.5 m |

These estimates were calculated from the measured $H_s$ using the empirical relations proposed by Forristal (1978). Table 2 also represents type A wave statistics and the data from the Northern Baltic Proper permanent wave buoy cover measurements from September 1996 to December 1999, including the severe storms in December 1999.

The severity of typical wave conditions in various areas is better compared using the significant wave height $H_s$ exceeded 10% of the ice-free time. These values have been adjusted for the length of the ice-free season. They represent statistics of type C. In Table 3 the data from the Northern Baltic Proper permanent wave buoy covers measurements September 1996 - September 1999. The severe storms in December 1999 have not been included in Table 3, because all the data required for it will not be available before this report is due.

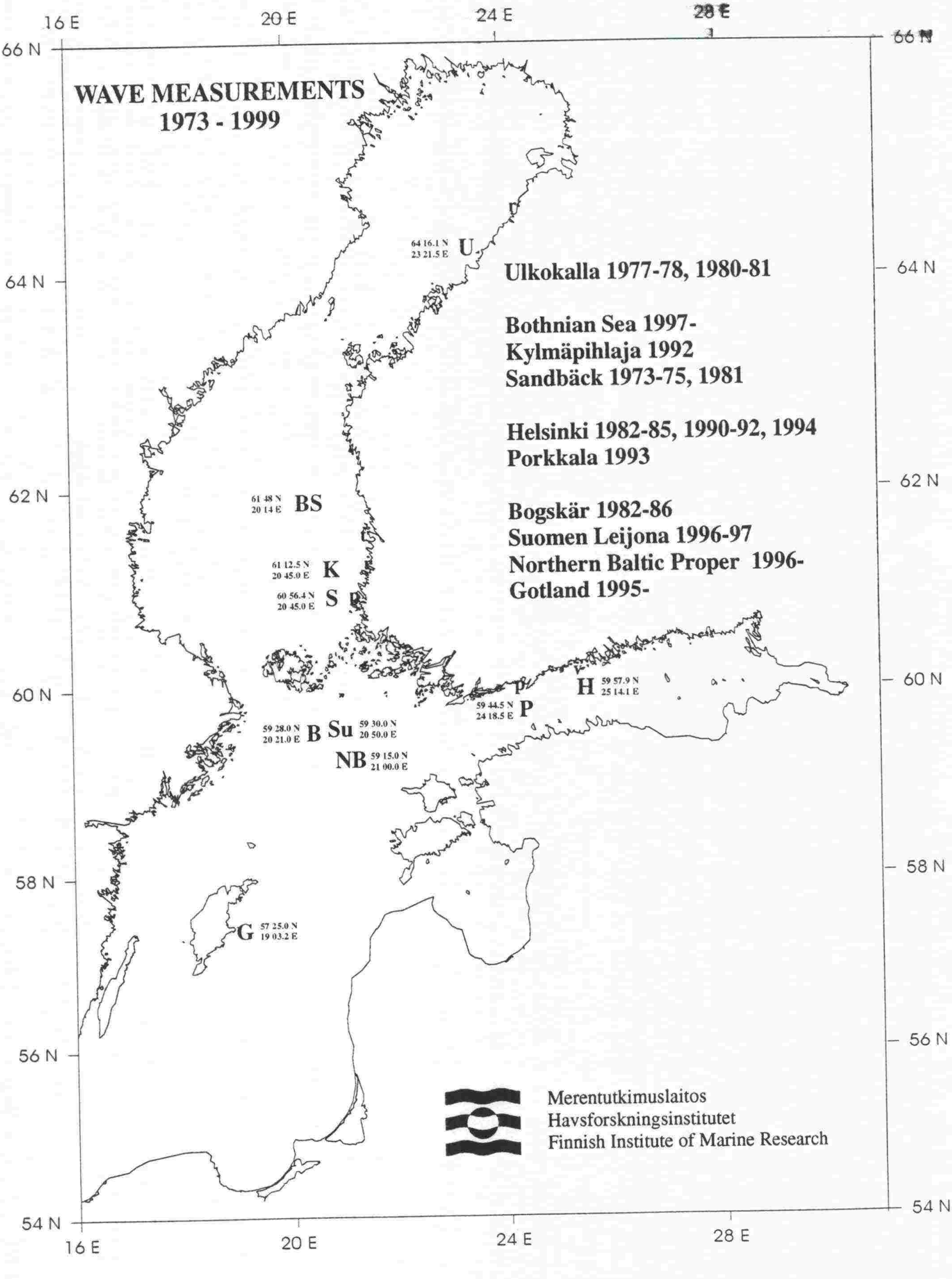


Figure 1: The locations and measuring periods of the Finnish Institute of Marine Research wave measurements.

Table 3: $H_s$ exceeded 10% of the ice-free time

| | |
|---|---|
| Northern Baltic Proper (permanent wave buoy) | 2.4 m |
| Northern Baltic Proper (Bogskär) | 2.7 m |
| Gulf of Finland (Helsinki - Tallinn) | 1.9 m |
| Southern Bothnian Sea | 2.4 m |
| Southern Bothnian Bay | 1.4 m |

# 3 Geographical distribution of wave heights along the route Helsinki - Stockholm

The shape of the Gulf of Finland restricts high waves to a narrow angle coming from the Baltic Proper. Moreover, the maximum height that waves can grow off Helsinki is limited by wave refraction. The U-shaped bottom of the Gulf of Finland refracts long waves towards the south and north coasts, and prevents waves with $H_s$ over 4 m from arriving at the longitude Helsinki - Tallinn (Pettersson, 1992). Figure 2 shows how wave height is reduced by refraction as the waves progress from the Baltic Proper to the Gulf of Finland. The reduction is approximately linear with the distance from Hanko to Helsinki for waves of period 8 s coming from the South-West. If the period is much longer, the reduction takes place already in the mouth of the Gulf of Finland.

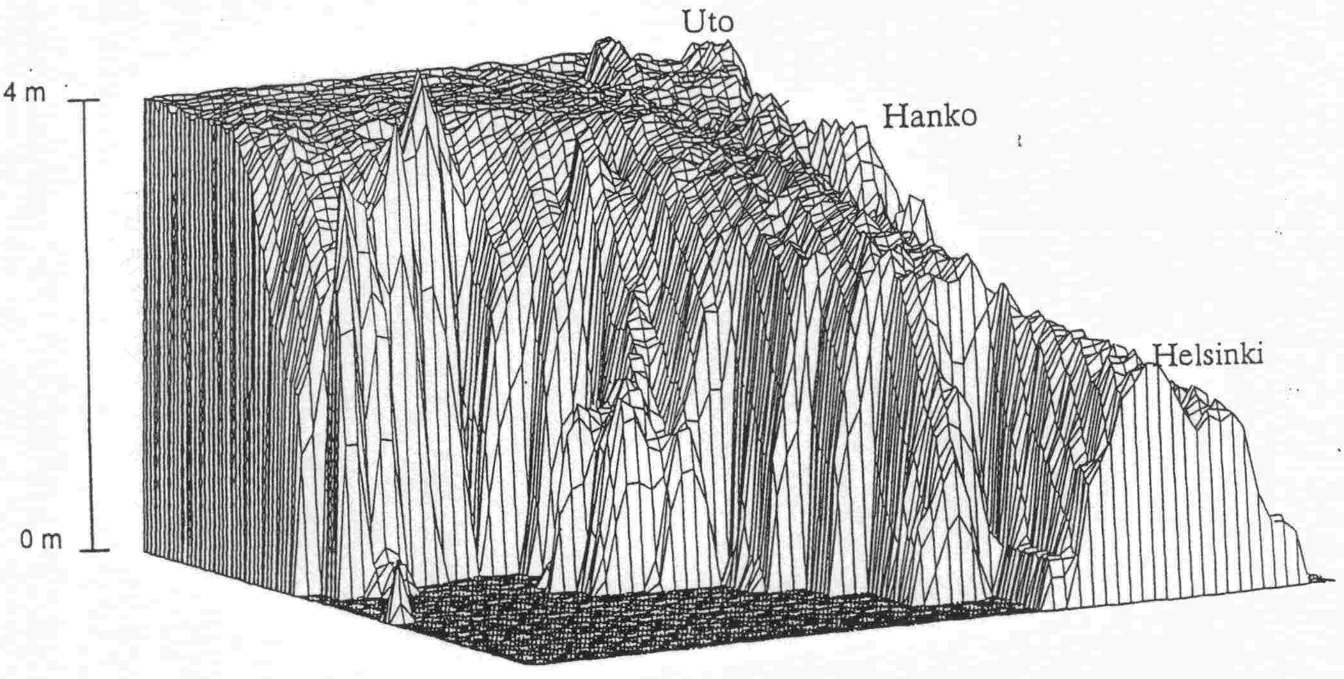


Figure 2: The reduction of wave height by spreading and refraction for waves coming into the Gulf of Finland from the Northern Baltic Proper. Incident wave height is assumed to be 4m, the period 8s, and the direction 260°.

# 4 Measured wave statistics in the Northern Baltic Proper

## 4.1 Measured wave statistics from the Northern Baltic Proper wave buoy

Since September 1996 FIMR has made wave measurements by a directional wave-rider buoy at 59°15' N 29°00' E, in the middle of the Northern Baltic Proper (Fig. 1). The measurements are nearly continuous and have only few gaps, with the exception the period when there is risk of ice. The measuring place is in water about 100 m deep, and therefore free from shallow water effects.

Table 4 is the type A scatter diagram from the Northern Baltic Proper wave buoy. Only measured data is taken into account in this type of statistics, and no corrections have been made to compensate the uneven distribution of missing values. The measurements were made approximately every hour. The table gives the number of hours that given conditions have prevailed when measurements have been made.

It should be noted that the severe storms in December 1999 have not been included in the data, because the data from October 1999 – December 1999 will not be available for statistical calculations before this report is due. When this data is included the statistics will show higher extreme waves than those indicated by tables 4 ... 6.

Table 5 is the type C scatter diagram from the Northern Baltic Proper. Only the part of the year when the sea is ice-free during an average winter has ben taken into account when statistics were calculated. Missing values during the ice-free season have been estimated from the seasonal distributions. This means that the table gives the number of hours that given conditions are expected to prevail during three years.

Because Table 5 gives hours rather than percentages it is identical with the type B statistics except for the two bottom lines (0 to 0.25, and the total), which will be different in type B statistics.

Note that Tables 4 and 5 are almost identical. This reflects the small number of gaps during the ice-free period in this data.

Table 6 shows the exceedence probabilities and hours from the Northern Baltic Proper permanent wave buoy. For convenience the probabilities are given both as percents and parts per million, as well as hours per 3 years and hours per 100 years.

Table 6 is type C statistics: only the part of the year when the sea is ice-free during an average winter is taken into account in calculating the statistics. Missing values during the ice-free season have been estimated from the seasonal distributions.

The numbers in Table 6 for hours per 3 years and hours per 100 years are identical to type B statistics with the exception of the bottom line. On the other hand, none of the numbers for the percents and ppms are equal to type B statistics.

Table 4: Wave data from Northern Baltic Proper 59°15.0 N 21°00.0 E. September 1996 – September 1999. All directions.

In this table the middle of the range of the peak wave period $T_p$ is shown: 2s means $T_p < 2.5$s, 3s means $2.5\text{s} < T_p < 3.5$s etc.

| significant wave height [m] | peak wave period [s] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | tot |
| 7.75 : 8.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.50 : 7.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.25 : 7.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.00 : 7.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.75 : 7.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 6.50 : 6.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.25 : 6.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 6.00 : 6.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 4 |
| 5.75 : 6.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1 | 0 | 5 |
| 5.50 : 5.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 3 |
| 5.25 : 5.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 0 | 0 | 11 |
| 5.00 : 5.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 6 | 0 | 0 | 7 |
| 4.75 : 5.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 | 1 | 0 | 9 |
| 4.50 : 4.75 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 19 | 28 | 2 | 0 | 53 |
| 4.25 : 4.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 3 | 1 | 0 | 20 |
| 4.00 : 4.25 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 28 | 21 | 4 | 0 | 74 |
| 3.75 : 4.00 | 0 | 0 | 0 | 0 | 0 | 4 | 47 | 42 | 24 | 4 | 0 | 121 |
| 3.50 : 3.75 | 0 | 0 | 0 | 0 | 0 | 5 | 97 | 78 | 29 | 2 | 0 | 211 |
| 3.25 : 3.50 | 0 | 0 | 0 | 0 | 0 | 17 | 120 | 52 | 13 | 1 | 0 | 203 |
| 3.00 : 3.25 | 0 | 0 | 0 | 0 | 2 | 63 | 134 | 38 | 16 | 1 | 0 | 254 |
| 2.75 : 3.00 | 0 | 0 | 0 | 0 | 8 | 105 | 151 | 28 | 8 | 0 | 0 | 300 |
| 2.50 : 2.75 | 0 | 0 | 0 | 0 | 62 | 299 | 245 | 63 | 7 | 1 | 1 | 678 |
| 2.25 : 2.50 | 0 | 0 | 0 | 3 | 104 | 279 | 117 | 29 | 2 | 1 | 0 | 535 |
| 2.00 : 2.25 | 0 | 0 | 0 | 23 | 310 | 432 | 129 | 22 | 4 | 0 | 0 | 920 |
| 1.75 : 2.00 | 0 | 0 | 1 | 84 | 572 | 386 | 117 | 31 | 3 | 1 | 0 | 1195 |
| 1.50 : 1.75 | 0 | 0 | 5 | 432 | 965 | 396 | 106 | 27 | 9 | 1 | 0 | 1941 |
| 1.25 : 1.50 | 0 | 0 | 42 | 1000 | 851 | 212 | 70 | 5 | 1 | 0 | 0 | 2181 |
| 1.00 : 1.25 | 0 | 2 | 260 | 1093 | 529 | 98 | 42 | 13 | 0 | 0 | 0 | 2037 |
| 0.75 : 1.00 | 0 | 42 | 1251 | 1390 | 397 | 97 | 36 | 7 | 2 | 0 | 0 | 3222 |
| 0.50 : 0.75 | 2 | 490 | 1596 | 754 | 203 | 68 | 21 | 0 | 0 | 0 | 0 | 3134 |
| 0.25 : 0.50 | 208 | 1386 | 1134 | 476 | 216 | 96 | 9 | 2 | 15 | 0 | 0 | 3542 |
| 0.00 : 0.25 | 174 | 301 | 257 | 211 | 297 | 80 | 4 | 3 | 7 | 2 | 0 | 1336 |
| total | 384 | 2221 | 4546 | 5466 | 4516 | 2637 | 1470 | 510 | 219 | 28 | 1 | 21998 |

Table 5: Wave data from Northern Baltic Proper 59°15.0 N 21°00.0 E. Missing values predicted by seasonal distributions. September 1996 – September 1999. All directions.

In this table the middle of the range of the peak wave period $T_p$ is shown: 2s means $T_p < 2.5$s, 3s means 2.5s $< T_p <$ 3.5s etc.

| significant wave height [m] | peak wave period [s] 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | tot |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7.75 : 8.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.50 : 7.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.25 : 7.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.00 : 7.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.75 : 7.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 6.50 : 6.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.25 : 6.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 6.00 : 6.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 4 |
| 5.75 : 6.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1 | 0 | 5 |
| 5.50 : 5.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 3 |
| 5.25 : 5.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 7 | 0 | 0 | 11 |
| 5.00 : 5.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 6 | 0 | 0 | 7 |
| 4.75 : 5.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 | 1 | 0 | 9 |
| 4.50 : 4.75 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 20 | 28 | 2 | 0 | 54 |
| 4.25 : 4.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 3 | 1 | 0 | 21 |
| 4.00 : 4.25 | 0 | 0 | 0 | 0 | 0 | 0 | 22 | 30 | 22 | 4 | 0 | 79 |
| 3.75 : 4.00 | 0 | 0 | 0 | 0 | 0 | 5 | 50 | 45 | 26 | 4 | 0 | 130 |
| 3.50 : 3.75 | 0 | 0 | 0 | 0 | 0 | 6 | 105 | 83 | 31 | 2 | 0 | 226 |
| 3.25 : 3.50 | 0 | 0 | 0 | 0 | 0 | 18 | 129 | 54 | 14 | 1 | 0 | 217 |
| 3.00 : 3.25 | 0 | 0 | 0 | 0 | 2 | 67 | 146 | 41 | 17 | 1 | 0 | 274 |
| 2.75 : 3.00 | 0 | 0 | 0 | 0 | 8 | 112 | 163 | 30 | 8 | 0 | 0 | 321 |
| 2.50 : 2.75 | 0 | 0 | 0 | 0 | 65 | 312 | 260 | 67 | 8 | 1 | 1 | 714 |
| 2.25 : 2.50 | 0 | 0 | 0 | 3 | 109 | 294 | 126 | 31 | 2 | 1 | 0 | 567 |
| 2.00 : 2.25 | 0 | 0 | 0 | 25 | 328 | 454 | 138 | 23 | 4 | 0 | 0 | 972 |
| 1.75 : 2.00 | 0 | 0 | 1 | 89 | 597 | 404 | 122 | 33 | 3 | 1 | 0 | 1250 |
| 1.50 : 1.75 | 0 | 0 | 5 | 449 | 1003 | 413 | 112 | 28 | 9 | 1 | 0 | 2021 |
| 1.25 : 1.50 | 0 | 0 | 43 | 1026 | 887 | 224 | 74 | 5 | 1 | 0 | 0 | 2259 |
| 1.00 : 1.25 | 0 | 2 | 259 | 1114 | 543 | 104 | 45 | 13 | 0 | 0 | 0 | 2081 |
| 0.75 : 1.00 | 0 | 42 | 1259 | 1404 | 407 | 101 | 40 | 8 | 2 | 0 | 0 | 3265 |
| 0.50 : 0.75 | 2 | 490 | 1587 | 759 | 210 | 69 | 22 | 0 | 0 | 0 | 0 | 3140 |
| 0.25 : 0.50 | 199 | 1384 | 1133 | 478 | 215 | 97 | 9 | 2 | 16 | 0 | 0 | 3534 |
| 0.00 : 0.25 | 171 | 296 | 249 | 205 | 283 | 77 | 4 | 3 | 7 | 2 | 0 | 1298 |
| total | 372 | 2214 | 4538 | 5553 | 4658 | 2756 | 1571 | 541 | 229 | 28 | 1 | 22462 |

Table 6: Wave data from Northern Baltic Proper 59°15.0 N 21°00.0 E. Missing values predicted by seasonal distributions. September 1996 – September 1999. All directions.

| Hs | % | ppm | h/3 years | h/100 years |
|---|---|---|---|---|
| 7.25 | 0.0 | 0 | 0 | 0 |
| 7.00 | 0.0 | 0 | 0 | 0 |
| 6.75 | 0.0 | 45 | 1 | 32 |
| 6.50 | 0.0 | 45 | 1 | 32 |
| 6.25 | 0.0 | 89 | 2 | 65 |
| 6.00 | 0.0 | 267 | 6 | 194 |
| 5.75 | 0.0 | 490 | 11 | 355 |
| 5.50 | 0.1 | 623 | 14 | 452 |
| 5.25 | 0.1 | 1113 | 25 | 807 |
| 5.00 | 0.1 | 1425 | 32 | 1033 |
| 4.75 | 0.2 | 1825 | 41 | 1324 |
| 4.50 | 0.4 | 4229 | 95 | 3068 |
| 4.25 | 0.5 | 5164 | 116 | 3746 |
| 4.00 | 0.9 | 8681 | 195 | 6297 |
| 3.75 | 1.4 | 14468 | 325 | 10495 |
| 3.50 | 2.5 | 24528 | 551 | 17793 |
| 3.25 | 3.4 | 34188 | 768 | 24800 |
| 3.00 | 4.6 | 46385 | 1042 | 33648 |
| 2.75 | 6.1 | 60675 | 1363 | 44014 |
| 2.50 | 9.2 | 92459 | 2077 | 67070 |
| 2.25 | 11.8 | 117699 | 2644 | 85379 |
| 2.00 | 16.1 | 160969 | 3616 | 116767 |
| 1.75 | 21.7 | 216613 | 4866 | 157131 |
| 1.50 | 30.7 | 306579 | 6887 | 222393 |
| 1.25 | 40.7 | 407140 | 9146 | 295340 |
| 1.00 | 50.0 | 499777 | 11227 | 362539 |
| 0.75 | 64.5 | 645121 | 14492 | 467971 |
| 0.50 | 78.5 | 784900 | 17632 | 569367 |
| 0.25 | 94.2 | 942219 | 21166 | 683485 |
| 0.00 | 100.0 | 1000000 | 22464 | 725400 |

## 4.2 Measured wave statistics near Bogskär

During the years 1983 - 1986 FIMR and the Swedish Meteorological and Hydrological Institute (SMHI) made joint wave measurements near Bogskär at 59°28.0' N 20°21.0' E. These measurements were made by a non-directional waverider. The directional information is therefore based on wind direction data.

SMHI has made wave measurements since 1978 on Almagrundet at 59°09' N 19°07' E (Svensson, 1983). The place is about 25 km from the mainland, and therefore does not represent open-sea conditions in westerly and south-westerly wind directions. Comparison of wave statistics from Almagrundet and Bogskär shows that the wave climate at Almagrundet is generally much less severe than at Bogskär. Therefore the data cannot in general be used when defining the wave climate in the Northern Baltic Proper. However, during southerly winds the place seems fairly representative.

On the 13th and 14 January, 1984 there was an exceptionally severe storm. The waverider unfortunately failed before the peak of the storm. The significant wave height at that point was 6.7 m, and the peak period 9.8 s. As the storm continued, $H_s$ up to 7.7 m was measured at Almagrundet. The wave height before the failure of the waverider was lower at Almagrundet (because of the shorter fetch), and it is therefore likely that at least the same $H_s$ was encountered at Bogskär.

If the highest waves that cause the measuring equipment to fail are just left out the statistics will be biassed in a dangerous way. Therefore the data from Almagrundet during this particular storm has been included. The Almagrundet data is presented in parenthesis in the tables.

Parametric wave model calculations based on wind speed data from Utö and Nyhamn from the years 1961 - 1999 indicate that the 1984 storm event is considerably less common than the Bogskär data alone suggests. Calculations show only four such events: the January 1984 storm, another in January 1993, and two in December 1999.

Table 7 is the type A scatter diagram from Bogskär. Only measured data is taken into account. No corrections have been made to compensate the uneven distribution of missing values. The measurements were made every hour, and therefore the numbers state how many hours the given wave conditions have lasted.

Table 8 is the type C scatter diagram from Bogskär. Only the part of the year when the sea is ice-free during an average winter is taken into account in calculating the statistics. Missing values during the ice-free season have been estimated from the seasonal distributions.

The total measuring time during the years 1982 - 1986 is 14630 hours, or about 2 years of uninterrupted measurements. The measuring times are, however, concentrated in the autumn season, and three autumns are well covered. For this reason we have adjusted the total measuring time in Table 8 to 3 years.

As mentioned above, the January 1984 storm seems to be a once-in-a-decade event that has by chance been captured by the measurements. The data from Almagrundet has been weighted as once in 10 years in the seasonally adjusted statistics. The data from Bogskär during the growth phase of that storm has been weighted as once in three years after $H_s$ exceeded 6 m. These deviations from the formal adjustment procedure are justified by parametric wave model calculations based on 39 years' wind statistics. The wave model uses the growth curves given by Kahma and Calkoen (1994).

Table 9 shows the exceedence probabilities and hours from Bogskär.

Table 9 is of type C statistics: only the part of the year when the sea is ice-free during an average winter is taken into account in calculating the statistics. Missing values during the ice-free season have been estimated from the seasonal distribution. The data in parenthesis has been adjusted using model calculations and the measurements from the permanent wave buoy in the Northern Baltic Proper. The corresponding unadjusted data is shown in Table 10.

The values for hours per 3 years and hours per 100 years are identical to type B statistics with the exception of the bottom line.

Data in parenthesis are from Almagrundet and cover the period 1984-01-13 21:00 to 01-14 05:00. Northern Baltic Proper data from 1996...1999 and wave model hindcasts from the years 1961 – 1999 have been taken into account when estimating the adjusted probability of the 1984-01-14 storm data.

Table 7: Wave data from Bogskär 59°28.0 N 20°21.0 E 1982 –1986. All directions. In this table the middle of the range of the peak wave period $T_p$ is shown: 2s means $T_p < 2.5$s, 3s means 2.5s $< T_p <$ 3.5s etc. Data in parenthesis are from Almagrundet 1984-01-13 21:00 - 01-14 05:00. Data from the Northern Baltic Proper 1996...1999 and wave model hindcasts from the years 1961...1999 have been taken into account when estimating the adjusted probability of the 1984-01-14 storm data.

| significant wave height [m] | peak wave period [s] 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | tot |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7.75:8.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.50:7.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | (1) | (1) |
| 7.25:7.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.00:7.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | (2) | (1) | 0 | (3) |
| 6.75:7.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.50:6.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 6.25:6.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | (1) | 0 | (1) |
| 6.00:6.25 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | (2) | 0 | 0 | (5) |
| 5.75:6.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | (1) | 0 | 0 | (2) |
| 5.50:5.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 3 |
| 5.25:5.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 1 | 0 | 0 | 0 | 8 |
| 5.00:5.25 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 7 | 0 | 0 | 0 | 0 | 9 |
| 4.75:5.00 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 8 | 3 | 0 | 0 | 0 | 12 |
| 4.50:4.75 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 9 | 2 | 0 | 0 | 0 | 17 |
| 4.25:4.50 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 21 | 1 | 0 | 0 | 0 | 32 |
| 4.00:4.25 | 0 | 0 | 0 | 0 | 0 | 3 | 23 | 33 | 1 | 0 | 0 | 0 | 60 |
| 3.75:4.00 | 0 | 0 | 0 | 0 | 3 | 10 | 44 | 29 | 1 | 0 | 0 | 0 | 87 |
| 3.50:3.75 | 0 | 0 | 0 | 0 | 5 | 37 | 52 | 13 | 1 | 0 | 0 | 0 | 108 |
| 3.25:3.50 | 0 | 0 | 0 | 0 | 5 | 49 | 105 | 17 | 1 | 0 | 0 | 0 | 177 |
| 3.00:3.25 | 0 | 0 | 0 | 0 | 17 | 83 | 126 | 11 | 1 | 0 | 0 | 0 | 238 |
| 2.75:3.00 | 0 | 0 | 0 | 1 | 39 | 145 | 117 | 12 | 1 | 0 | 0 | 0 | 315 |
| 2.50:2.75 | 0 | 0 | 0 | 0 | 83 | 172 | 80 | 8 | 0 | 0 | 0 | 0 | 343 |
| 2.25:2.50 | 0 | 0 | 0 | 9 | 169 | 223 | 75 | 5 | 0 | 0 | 0 | 0 | 481 |
| 2.00:2.25 | 0 | 0 | 0 | 38 | 312 | 261 | 67 | 4 | 0 | 0 | 0 | 0 | 682 |
| 1.75:2.00 | 0 | 0 | 0 | 127 | 373 | 188 | 35 | 7 | 0 | 0 | 0 | 0 | 730 |
| 1.50:1.75 | 0 | 0 | 9 | 351 | 441 | 138 | 23 | 1 | 0 | 0 | 0 | 0 | 963 |
| 1.25:1.50 | 0 | 0 | 81 | 708 | 465 | 78 | 16 | 1 | 0 | 0 | 0 | 0 | 1349 |
| 1.00:1.25 | 0 | 2 | 416 | 852 | 400 | 68 | 7 | 6 | 0 | 0 | 0 | 0 | 1751 |
| 0.75:1.00 | 25 | 54 | 914 | 723 | 241 | 58 | 9 | 0 | 0 | 0 | 0 | 0 | 2024 |
| 0.50:0.75 | 147 | 443 | 918 | 559 | 162 | 50 | 21 | 5 | 5 | 0 | 0 | 0 | 2310 |
| 0.25:0.50 | 192 | 692 | 562 | 206 | 74 | 25 | 31 | 27 | 10 | 3 | 0 | 0 | 1822 |
| 0.00:0.25 | 185 | 321 | 224 | 103 | 65 | 58 | 73 | 50 | 11 | 6 | 0 | 0 | 1096 |
| total | 549 | 1512 | 3124 | 3677 | 2854 | 1647 | 923 | 286 | 41 | 14 | 2 | 1 | 14630 |

Table 8: Wave data from Bogskär 59°28.0 N 20°21.0 E 1982 – 1986. Missing values predicted by seasonal distributions. Unit: hours per 3 years. All directions.
In this table the middle of the range of the peak wave period $T_p$ is shown: 2s means $T_p < 2.5$s, 3s means $2.5\text{s} < T_p < 3.5$s etc. Data in parenthesis are from Almagrundet 1984-01-13 21:00 to 01-14 05:00. Data from the Northern Baltic Proper 1996...1999 and wave model hindcasts from the years 1961...1999 have been taken into account when estimating the adjusted probability of the 1984-01-14 storm data.

| significant | | | | | peak wave period [s] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| wave height [m] | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | tot |
| 7.75:8.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.50:7.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | (0.3) | (0.3) |
| 7.25:7.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.00:7.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | (0.6) | (0.3) | 0 | (0.9) |
| 6.75:7.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.50:6.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 6.25:6.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | (0.3) | 0 | (0.3) |
| 6.00:6.25 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | (0.6) | 0 | 0 | (3.6) |
| 5.75:6.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | (0.3) | 0 | 0 | (1.3) |
| 5.50:5.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1 | 0 | 0 | 0 | 5 |
| 5.25:5.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 1 | 0 | 0 | 0 | 17 |
| 5.00:5.25 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 14 | 0 | 0 | 0 | 0 | 18 |
| 4.75:5.00 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 14 | 7 | 0 | 0 | 0 | 22 |
| 4.50:4.75 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 12 | 4 | 0 | 0 | 0 | 31 |
| 4.25:4.50 | 0 | 0 | 0 | 0 | 0 | 3 | 18 | 35 | 3 | 0 | 0 | 0 | 59 |
| 4.00:4.25 | 0 | 0 | 0 | 0 | 0 | 5 | 44 | 54 | 1 | 0 | 0 | 0 | 105 |
| 3.75:4.00 | 0 | 0 | 0 | 0 | 4 | 25 | 76 | 44 | 3 | 0 | 0 | 0 | 152 |
| 3.50:3.75 | 0 | 0 | 0 | 0 | 13 | 86 | 107 | 17 | 3 | 0 | 0 | 0 | 226 |
| 3.25:3.50 | 0 | 0 | 0 | 0 | 14 | 98 | 206 | 28 | 1 | 0 | 0 | 0 | 347 |
| 3.00:3.25 | 0 | 0 | 0 | 0 | 34 | 141 | 248 | 19 | 3 | 0 | 0 | 0 | 445 |
| 2.50:2.75 | 0 | 0 | 0 | 0 | 167 | 283 | 145 | 15 | 0 | 0 | 0 | 0 | 585 |
| 2.75:3.00 | 0 | 0 | 0 | 3 | 76 | 261 | 219 | 23 | 3 | 0 | 0 | 0 | 610 |
| 2.25:2.50 | 0 | 0 | 0 | 21 | 279 | 353 | 132 | 10 | 0 | 0 | 0 | 0 | 794 |
| 2.00:2.25 | 0 | 0 | 0 | 79 | 500 | 420 | 124 | 8 | 0 | 0 | 0 | 0 | 1132 |
| 1.75:2.00 | 0 | 0 | 0 | 222 | 573 | 298 | 64 | 17 | 0 | 0 | 0 | 0 | 1174 |
| 1.50:1.75 | 0 | 0 | 24 | 582 | 657 | 214 | 47 | 3 | 0 | 0 | 0 | 0 | 1527 |
| 1.25:1.50 | 0 | 0 | 151 | 1128 | 671 | 119 | 35 | 3 | 0 | 0 | 0 | 0 | 2106 |
| 1.00:1.25 | 0 | 6 | 666 | 1290 | 575 | 103 | 11 | 17 | 0 | 0 | 0 | 0 | 2667 |
| 0.75:1.00 | 32 | 87 | 1311 | 1017 | 352 | 86 | 14 | 0 | 0 | 0 | 0 | 0 | 2899 |
| 0.50:0.75 | 190 | 668 | 1319 | 787 | 240 | 79 | 30 | 7 | 9 | 0 | 0 | 0 | 3329 |
| 0.25:0.50 | 254 | 998 | 806 | 314 | 128 | 43 | 41 | 38 | 13 | 4 | 0 | 0 | 2637 |
| 0.00:0.25 | 260 | 464 | 324 | 146 | 86 | 75 | 95 | 67 | 16 | 9 | 0 | 0 | 1543 |

Table 9: Wave data from Bogskär 59°28.0 N 20°21.0 E 1982 – 1986. Exceedence probabilities. Missing values predicted by seasonal distributions. All directions. Data in parenthesis are from Almagrundet 1984-01-13 21:00 to 01-14 05:00. Northern Baltic Proper data from 1996...1999 and wave model hindcasts from the years 1961...1999 have been taken into account when estimating the adjusted probability of the 1984-01-14 storm data.

| Hs | % | ppm | h/3 years | h/100 years |
|---|---|---|---|---|
| 7.75 | 0.0 | 0 | 0 | 0 |
| 7.50 | 0.0 | (13) | 0 | (10) |
| 7.25 | 0.0 | (13) | 0 | (10) |
| 7.00 | 0.0 | (53) | (1) | (39) |
| 6.75 | 0.0 | (53) | (1) | (39) |
| 6.50 | 0.0 | (98) | (2) | (71) |
| 6.25 | 0.0 | (111) | (3) | (81) |
| 6.00 | 0.0 | (272) | (6) | (197) |
| 5.75 | 0.0 | (330) | (7) | (239) |
| 5.50 | 0.1 | 553 | 12 | 401 |
| 5.25 | 0.1 | 1310 | 29 | 951 |
| 5.00 | 0.2 | 2113 | 47 | 1532 |
| 4.75 | 0.3 | 3093 | 69 | 2244 |
| 4.50 | 0.4 | 4475 | 100 | 3246 |
| 4.25 | 0.7 | 7104 | 159 | 5153 |
| 4.00 | 1.2 | 11784 | 264 | 8548 |
| 3.75 | 1.9 | 18558 | 416 | 13462 |
| 3.50 | 2.9 | 28631 | 642 | 20769 |
| 3.25 | 4.4 | 44096 | 989 | 31987 |
| 3.00 | 6.4 | 63929 | 1434 | 46374 |
| 2.75 | 9.0 | 90002 | 2019 | 65287 |
| 2.50 | 11.7 | 117188 | 2629 | 85008 |
| 2.25 | 15.3 | 152576 | 3423 | 110678 |
| 2.00 | 20.3 | 203027 | 4555 | 147276 |
| 1.75 | 25.5 | 255350 | 5729 | 185231 |
| 1.50 | 32.3 | 323406 | 7256 | 234599 |
| 1.25 | 41.7 | 417268 | 9362 | 302686 |
| 1.00 | 53.6 | 536132 | 12029 | 388910 |
| 0.75 | 66.5 | 665336 | 14928 | 482634 |
| 0.50 | 81.4 | 813704 | 18257 | 590261 |
| 0.25 | 93.1 | 931231 | 20894 | 675515 |
| 0.00 | 100.0 | 1000000 | 22437 | 725400 |

# 5 Extrapolated wave statistics

## 5.1 Method of extrapolation

The aim is to determine the upper-limit extrapolation, defined so that it is unlikely to be exceeded when more data will be available. This extrapolation is inteded to be used as a conservative estimate.

The measured scatter diagrams show that at the location of the buoy in the Northern Baltic Proper the wave period is longer at the same significant wave height than at Bogskär. In addition, the probability of high waves seems larger than at Bogskär. The upper-limit extrapolation is therefore based on the data from Bogskär without adjusting the probability of the January 1984 storm. This distribution is presented in Table 10.

To extrapolate the $H_s$ statistics we have used the Weibull distribution.

The scatter diagram extrapolation is based on the fact that in extreme wave conditions the wave spectrum has in most cases a self-similar form that can be characterized by the significant wave height $H_s$ and the peak period $T_p$. This is because only in close to ideal conditions it is possible for the waves to grow to the maximum height allowed by the wind speed and fetch.

From the approximate self-similarity it follows that the significant slope $H_s/(gT_p^2)$ is approximately constant. In the literature an empirically determined limit $H_s/(gT_p^2) =$ 0.00776 has been reported in Buckley (1990). In the Bogskär data the mean value in the case of high waves was about 0.006. At a given $H_s$ the inverse $gT_p^2/H_s$ was found to be approximately normally distributed.

The empirical data from Bogskär gave the following parameters of $gT_p^2/H_s$ for the best fit: mean 173 and standard deviation 30. From these a two-dimensional Weibull-Gaussian distribution was constructed.

The upper-limit extrapolation is presented in Table 11 in the same units as data in Tables 8 and 10. Comparing Table 11 with the observed data in Table 8 and Table 10 it can be seen that the extrapolation reasonably well describes the observations. It is higher than the observed data in Table 8 but does not follow the extreme values in Table 10 which stand out from the rest of the data.

Table 12 gives the upper-limit extrapolation in parts per million (ppm) of the ice-free time. It is statistics of type C. Table 13 gives the same extrapolation in hours per 100 years. It is at the same time statistics of type B and C.

Table 10: Wave data from Bogskär 59°28.0 N 20°21.0 E 1982 – 1986. Missing values predicted by seasonal distributions without taking into account model calculations. Unit: hours per 3 years. All directions.

In this table the middle of the range of the peak wave period $T_p$ is shown: 2s means $T_p < 2.5$s, 3s means $2.5\text{s} < T_p < 3.5$s etc.

| significant wave height [m] | peak wave period [s] 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | tot |
|---|---|---|---|---|---|---|---|---|---|
| 7.75 : 8.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.50 : 7.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | (3) | (3) |
| 7.25 : 7.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.00 : 7.25 | 0 | 0 | 0 | 0 | 0 | (6) | (3) | 0 | (8) |
| 6.75 : 7.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.50 : 6.75 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 |
| 6.25 : 6.50 | 0 | 0 | 0 | 0 | 0 | 0 | (3) | 0 | (3) |
| 6.00 : 6.25 | 0 | 0 | 3 | 6 | 0 | (6) | 0 | 0 | (14) |
| 5.75 : 6.00 | 0 | 0 | 0 | 1 | 0 | (3) | 0 | 0 | (4) |
| 5.50 : 5.75 | 0 | 0 | 0 | 4 | 1 | 0 | 0 | 0 | 5 |
| 5.25 : 5.50 | 0 | 0 | 0 | 15 | 1 | 0 | 0 | 0 | 17 |
| 5.00 : 5.25 | 0 | 0 | 4 | 14 | 0 | 0 | 0 | 0 | 18 |
| 4.75 : 5.00 | 0 | 0 | 1 | 14 | 7 | 0 | 0 | 0 | 22 |
| 4.50 : 4.75 | 0 | 0 | 15 | 12 | 4 | 0 | 0 | 0 | 31 |
| 4.25 : 4.50 | 0 | 3 | 18 | 35 | 3 | 0 | 0 | 0 | 59 |
| 4.00 : 4.25 | 0 | 5 | 44 | 54 | 1 | 0 | 0 | 0 | 105 |
| 3.75 : 4.00 | 4 | 25 | 76 | 44 | 3 | 0 | 0 | 0 | 152 |
| 3.50 : 3.75 | 13 | 86 | 107 | 17 | 3 | 0 | 0 | 0 | 226 |
| 3.25 : 3.50 | 14 | 98 | 206 | 28 | 1 | 0 | 0 | 0 | 347 |
| 3.00 : 3.25 | 34 | 141 | 248 | 19 | 3 | 0 | 0 | 0 | 445 |

Table 11: Extrapolated scatter diagram, upper-limit extrapolation. Unit: hours per 3 years. All directions.

In this table the middle of the range of the peak wave period $T_p$ is shown: 2s means $T_p < 2.5$s, 3s means $2.5\text{s} < T_p < 3.5$s etc.

| significant wave height [m] | peak wave period [s] 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|
| 7.75 : 8.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.50 : 7.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.25 : 7.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7.00 : 7.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6.75 : 7.00 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 6.50 : 6.75 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 6.25 : 6.50 | 0 | 0 | 0 | 0 | 1 | 2 | 1 | 0 |
| 6.00 : 6.25 | 0 | 0 | 0 | 1 | 2 | 2 | 1 | 0 |
| 5.75 : 6.00 | 0 | 0 | 0 | 2 | 4 | 3 | 0 | 0 |
| 5.50 : 5.75 | 0 | 0 | 1 | 3 | 6 | 3 | 0 | 0 |
| 5.25 : 5.50 | 0 | 0 | 2 | 6 | 9 | 3 | 0 | 0 |
| 5.00 : 5.25 | 0 | 0 | 3 | 11 | 12 | 3 | 0 | 0 |
| 4.75 : 5.00 | 0 | 1 | 6 | 18 | 14 | 2 | 0 | 0 |
| 4.50 : 4.75 | 0 | 2 | 13 | 28 | 15 | 1 | 0 | 0 |
| 4.25 : 4.50 | 0 | 5 | 25 | 40 | 13 | 1 | 0 | 0 |
| 4.00 : 4.25 | 1 | 10 | 45 | 50 | 9 | 0 | 0 | 0 |
| 3.75 : 4.00 | 2 | 23 | 76 | 54 | 5 | 0 | 0 | 0 |
| 3.50 : 3.75 | 5 | 48 | 116 | 47 | 2 | 0 | 0 | 0 |
| 3.25 : 3.50 | 13 | 98 | 153 | 31 | 0 | 0 | 0 | 0 |
| 3.00 : 3.25 | 34 | 183 | 165 | 14 | 0 | 0 | 0 | 0 |

Table 12: Extrapolated scatter diagram, upper-limit extrapolation. Unit: parts per million (ppm) All directions.

In this table the middle of the range of the peak wave period $T_p$ is shown: 2s means $T_p < 2.5$s, 3s means 2.5s $< T_p <$ 3.5s etc.

| significant wave height [m] | peak wave period [s] 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| 9.25: 9.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9.00: 9.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8.75: 9.00 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 8.50: 8.75 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| 8.25: 8.50 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 1 | 0 |
| 8.00: 8.25 | 0 | 0 | 0 | 0 | 1 | 2 | 4 | 2 | 1 | 0 |
| 7.75: 8.00 | 0 | 0 | 0 | 0 | 1 | 4 | 6 | 3 | 1 | 0 |
| 7.50: 7.75 | 0 | 0 | 0 | 1 | 3 | 8 | 9 | 4 | 0 | 0 |
| 7.25: 7.50 | 0 | 0 | 0 | 1 | 6 | 13 | 12 | 4 | 0 | 0 |
| 7.00: 7.25 | 0 | 0 | 0 | 3 | 11 | 21 | 17 | 4 | 0 | 0 |
| 6.75: 7.00 | 0 | 0 | 1 | 5 | 20 | 34 | 22 | 4 | 0 | 0 |
| 6.50: 6.75 | 0 | 0 | 2 | 11 | 36 | 52 | 25 | 3 | 0 | 0 |
| 6.25: 6.50 | 0 | 0 | 3 | 21 | 64 | 76 | 27 | 2 | 0 | 0 |
| 6.00: 6.25 | 0 | 1 | 7 | 42 | 109 | 102 | 27 | 1 | 0 | 0 |
| 5.75: 6.00 | 0 | 2 | 16 | 81 | 178 | 128 | 23 | 1 | 0 | 0 |
| 5.50: 5.75 | 0 | 4 | 33 | 154 | 276 | 145 | 17 | 0 | 0 | 0 |
| 5.25: 5.50 | 1 | 8 | 70 | 282 | 399 | 147 | 10 | 0 | 0 | 0 |
| 5.00: 5.25 | 1 | 18 | 146 | 496 | 539 | 129 | 5 | 0 | 0 | 0 |
| 4.75: 5.00 | 3 | 41 | 298 | 828 | 635 | 95 | 2 | 0 | 0 | 0 |
| 4.50: 4.75 | 7 | 93 | 594 | 1286 | 666 | 56 | 0 | 0 | 0 | 0 |
| 4.25: 4.50 | 17 | 210 | 1141 | 1825 | 593 | 25 | 0 | 0 | 0 | 0 |
| 4.00: 4.25 | 40 | 470 | 2078 | 2298 | 426 | 8 | 0 | 0 | 0 | 0 |
| 3.75: 4.00 | 98 | 1038 | 3509 | 2477 | 232 | 1 | 0 | 0 | 0 | 0 |
| 3.50: 3.75 | 245 | 2221 | 5337 | 2174 | 87 | 0 | 0 | 0 | 0 | 0 |
| 3.25: 3.50 | 618 | 4507 | 7024 | 1445 | 19 | 0 | 0 | 0 | 0 | 0 |
| 3.00: 3.25 | 1557 | 8402 | 7568 | 652 | 2 | 0 | 0 | 0 | 0 | 0 |

Table 13: Extrapolated scatter diagram, upper-limit extrapolation. Unit: hours per 100 years. All directions.
In this table the middle of the range of the peak wave period $T_p$ is shown: 2s means $T_p < 2.5$s, 3s means $2.5\text{s} < T_p < 3.5$s etc.

| significant wave height [m] | peak wave period [s] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 9.25: 9.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9.00: 9.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8.75: 9.00 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 8.50: 8.75 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 8.25: 8.50 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 1 | 0 | 0 |
| 8.00: 8.25 | 0 | 0 | 0 | 0 | 1 | 2 | 3 | 2 | 0 | 0 |
| 7.75: 8.00 | 0 | 0 | 0 | 0 | 1 | 3 | 4 | 2 | 0 | 0 |
| 7.50: 7.75 | 0 | 0 | 0 | 0 | 2 | 5 | 6 | 3 | 0 | 0 |
| 7.25: 7.50 | 0 | 0 | 0 | 1 | 4 | 9 | 9 | 3 | 0 | 0 |
| 7.00: 7.25 | 0 | 0 | 0 | 2 | 8 | 16 | 12 | 3 | 0 | 0 |
| 6.75: 7.00 | 0 | 0 | 1 | 4 | 14 | 25 | 16 | 3 | 0 | 0 |
| 6.50: 6.75 | 0 | 0 | 1 | 8 | 26 | 38 | 18 | 2 | 0 | 0 |
| 6.25: 6.50 | 0 | 0 | 3 | 15 | 46 | 55 | 20 | 2 | 0 | 0 |
| 6.00: 6.25 | 0 | 1 | 5 | 30 | 79 | 74 | 19 | 1 | 0 | 0 |
| 5.75: 6.00 | 0 | 1 | 11 | 59 | 129 | 93 | 16 | 1 | 0 | 0 |
| 5.50: 5.75 | 0 | 3 | 24 | 111 | 200 | 106 | 12 | 0 | 0 | 0 |
| 5.25: 5.50 | 0 | 6 | 51 | 205 | 289 | 107 | 7 | 0 | 0 | 0 |
| 5.00: 5.25 | 1 | 13 | 106 | 360 | 384 | 94 | 4 | 0 | 0 | 0 |
| 4.75: 5.00 | 2 | 30 | 216 | 600 | 460 | 69 | 1 | 0 | 0 | 0 |
| 4.50: 4.75 | 5 | 67 | 431 | 933 | 483 | 41 | 0 | 0 | 0 | 0 |
| 4.25: 4.50 | 12 | 152 | 828 | 1324 | 430 | 18 | 0 | 0 | 0 | 0 |
| 4.00: 4.25 | 29 | 341 | 1507 | 1667 | 309 | 6 | 0 | 0 | 0 | 0 |
| 3.75: 4.00 | 71 | 753 | 2545 | 1797 | 168 | 1 | 0 | 0 | 0 | 0 |
| 3.50: 3.75 | 178 | 1611 | 3871 | 1577 | 63 | 0 | 0 | 0 | 0 | 0 |
| 3.25: 3.50 | 448 | 3269 | 5095 | 1049 | 14 | 0 | 0 | 0 | 0 | 0 |
| 3.00: 3.25 | 1129 | 6095 | 5490 | 473 | 2 | 0 | 0 | 0 | 0 | 0 |

# 6 Estimated wave conditions in the Åland Sea

The only part of the route between Turku and Stockholm that is exposed to open sea waves is in the Åland Sea. Even there only the waves coming from SSE and possibly NNW can be large. The short fetch effectively limits the wave growth from other directions. This means that as long as the ship retains its normal course between Turku and Stockholm it will not be exposed to high waves from the bow.

The following table gives estimates of the significant wave height when the probabilities of exceedence are 1%, 3%, 5%, and 10% . Only the open sea season (the time when the sea is free of ice at the point considered) is taken into account.

Calculation are based on the directionally stratified statistics at Bogskär using a wave model. The effect of the Åland archipelago and the decay in shallow water areas have been taken into account in these estimates. Estimates are of type C.

Table 14: Estimates of significant wave height in the Åland Sea and Bogskär

| | Åland Sea | Bogskär |
|---|---|---|
| % | $H_s$ | $H_s$ |
| 10 | 1.7 m | 2.7 |
| 5 | 2.0 m | 3.2 |
| 3 | 2.2 m | 3.5 |
| 1 | 2.6 m | 4.1 |
| A crude estimate of rare conditions: | | |
| 0.03 | 4.0 m | 5.7 |

# 7 Duration of high wave conditions

Tables 6 and 9 show that significant wave height 4 m is exceeded only about 1% of the time or about 70 hours per year. In addition, this time is not continuous but is split into short storms. Figure 3 shows how $H_s$ has varied in October 1998.

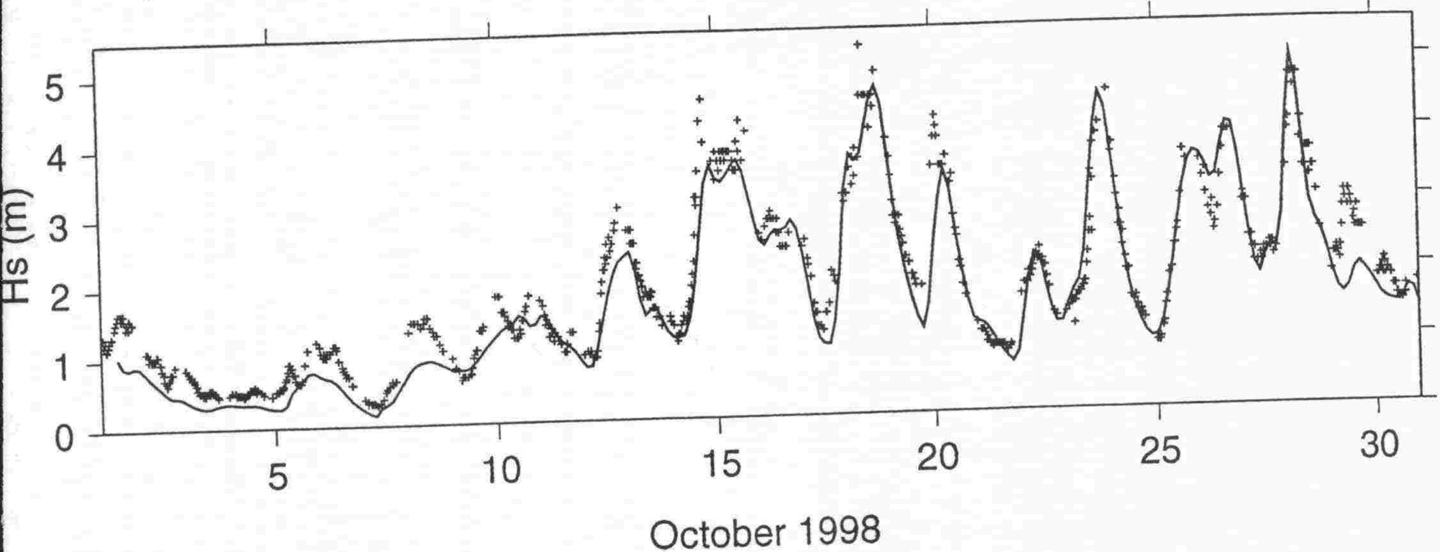


Figure 3: Significant wave height in October 1998 at the Northern Baltic Proper permanent wave buoy. Measurements and model hindcast.

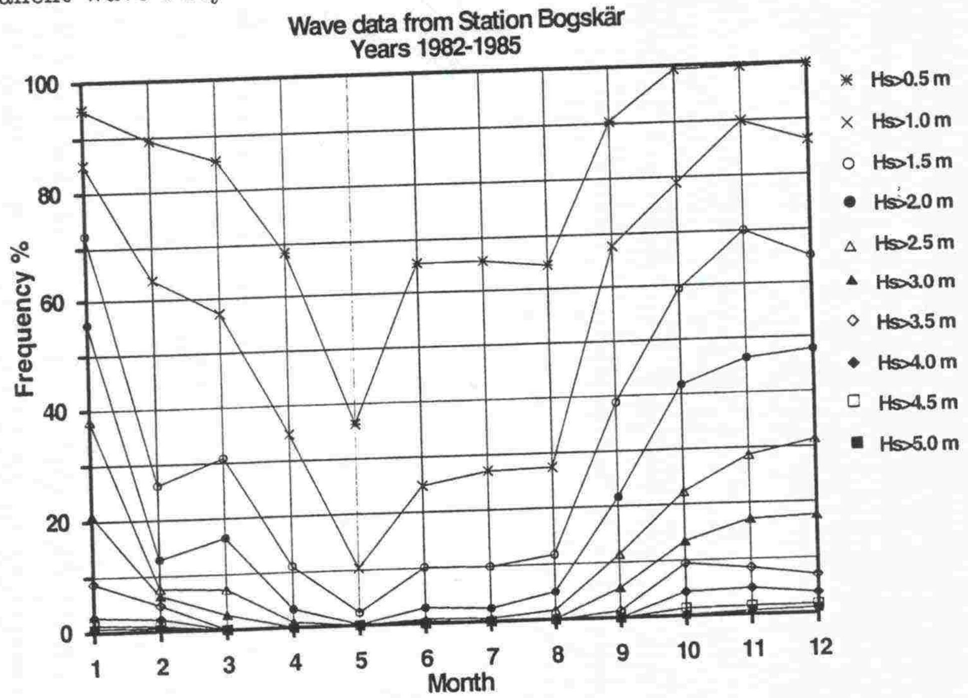


Figure 4: Probabilities of wave conditions in different months. Wave data from Bogskär 1982 – 1985.

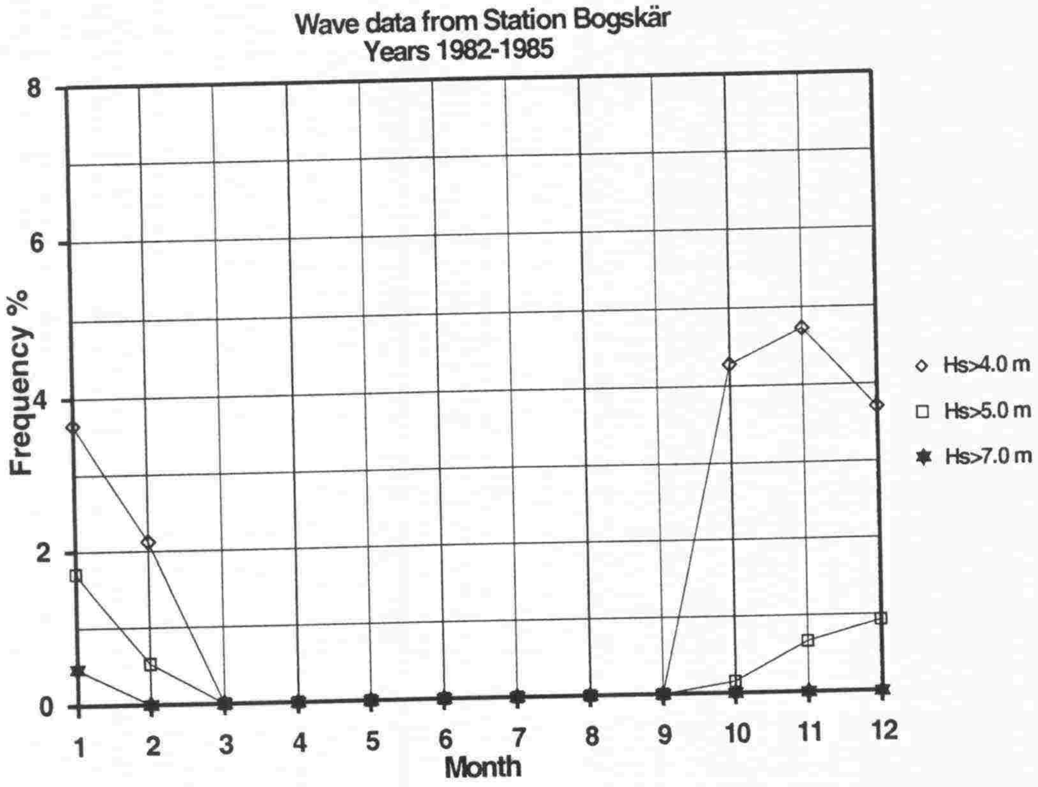


Figure 5: Probabilities of highest wave conditions in different months. Wave data from Bogskär 1982 – 1985.

Figures 4 and 5 show the duration of highest wave conditions in different seasons. While high waves can occur in all seasons, in practice they are restricted to autumn and winter time.

# 8 Operational wave measurements and forecasts

From September 1996 FIMR has made wave measurements by a directional wave-rider buoy at 59°15' N 29°00' E, in the middle of the Northern Baltic Proper. The data is transmitted by ARGOS satellites, and it is usually available within hours at the FIMR website and the Finnish Meteorological Institute's telephone service. FIMR attempts to keep the buoy operational uninterruptedly except for the period from January 27 to April 25 when there is a danger that drifting ice will damage the buoy.

A wave model nowcast is provided through the same channels when measured data is not available. An example of the FIMR wave model nowcast can be seen in Figure 3.

The accuracy of wave models depends in the first place on the accuracy of atmospheric models. Short-term wave forecasts are much more accurate than normal 24-hour and 48-hour forecasts.

Wave forecasts six hours ahead are as reliable as the nowcast in Figure 3. Because large waves do not grow fast, even more accurate forecasts than those presented in Figure 3 can be made for high waves by assimilating the measured wave height into the wave model and making the forecast available to the user just at the time it is needed for decisions.

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